

(19) World Intellectual Property Organization
International Bureau



(43) International Publication Date
24 December 2003 (24.12.2003)

PCT

(10) International Publication Number
WO 03/107463 A2

(51) International Patent Classification⁷: **H01M 8/00**

(21) International Application Number: PCT/GB03/02547

(22) International Filing Date: 13 June 2003 (13.06.2003)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
0213561.4 13 June 2002 (13.06.2002) GB

(71) Applicant (for all designated States except US): **ALSTOM**
[FR/TR]; 25 avenue Kléber, F-75116 Paris (FR).

(72) Inventor; and

(75) Inventor/Applicant (for US only): **LEAH, Robert, Timothy** [GB/GB]; Flat 2, 10 Ledbury Place, Croydon, Surrey CRO 1ET (GB).

(74) Agent: **DARGAVEL, Laurence, Peter**; Alstom Intellectual Property, Alstom Ltd, PO Box 30, Lichfield Road, Stafford ST17 4LN (GB).

(81) Designated States (*national*): AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CII, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SC, SD, SE, SG, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, YU, ZA, ZM, ZW.

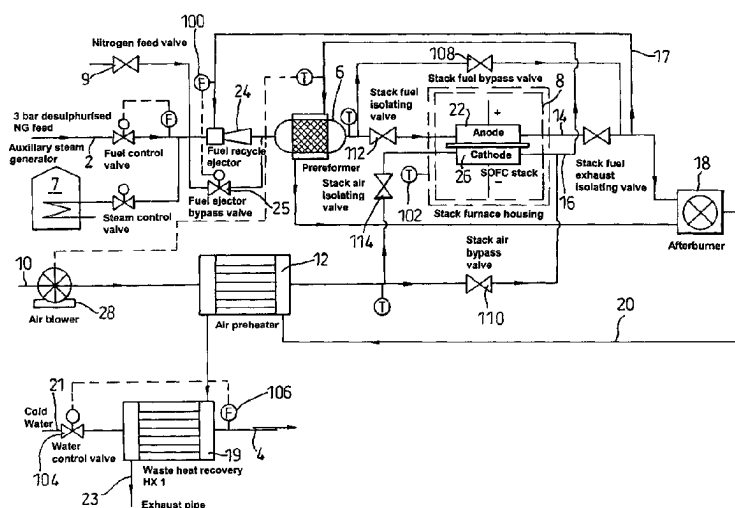
(84) Designated States (*regional*): ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CII, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IIU, IE, IT, LU, MC, NL, PT, RO, SE, SI, SK, TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— without international search report and to be republished upon receipt of that report

For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

(54) Title: FUEL CELL OPERATING CYCLES AND SYSTEMS



(57) Abstract: Operating cycles for fuel cell systems, particularly solid oxide fuel cell (SOFC) systems, include recirculation of at least a portion of exhaust gases (17) emitted from the anode and/or cathode sides of the fuel cell stack (8) and mixing them with fresh reactants (2, 10) before supply to the fuel cell. To control the temperature of the stack, bypass loops are used to allow a proportion of the oxidant to bypass an oxidant preheater (12) and/or the fuel cell stack. The relative proportions of fresh and recirculated fuel are maintained constant during normal operation of the system by controlling an ejector (24) which powers recirculation of the exhaust from the anode side of the stack.

FUEL CELL OPERATING CYCLES AND SYSTEMS

Field of the Invention

This invention relates to fuel cell systems and improved operating cycles for fuel cell systems, and in particular to systems including Solid Oxide Fuel Cells (SOFC's).

Background of the Invention

Of the various fuel cell types currently under development, solid oxide fuel cells (SOFCs) appear well suited to the demands of the stationary electrical power generation market. SOFCs may offer the highest electrical efficiency when operating on hydrocarbon fuels (in excess of 45%), so they can be expected to have the most competitive running costs. They will also offer fuel flexibility and security of supply since they can potentially be operated on a range of fuels, including pipeline natural gas and bio-mass, without a significant loss of efficiency or increase in system complexity and cost. With these attributes, and being essentially modular, SOFC systems will be highly attractive for the distributed power market where units can be configured and sized to meet a particular local power generation demand. High system efficiencies for SOFC should also make the biggest impact in reducing emissions of carbon dioxide which, combined with very low emissions of major local air pollutants (CO, NO_x and unburned hydrocarbons), will make them an extremely attractive generation technology as tighter emissions legislation is implemented. In order for SOFC systems to realise their potential in the stationary power generation market, they will have to achieve substantial cost reductions compared to systems demonstrated to date. The major cost saving for SOFC will be achieved by exploiting the potential for making systems simpler and more compact.

Low-temperature fuel cells (PEMFC, PAFC, etc) use noble-metal catalyst electrodes, which must be fed with a high purity hydrogen fuel. This requires a complex and expensive balance-of-plant (BOP) in order to provide the necessary pre-processing for hydrocarbon fuels. The energy consumed in performing this processing also limits the efficiency of these systems. By contrast, the high

operating temperature of SOFCs gives them the possibility of steam reforming methane to hydrogen and carbon monoxide within the fuel cell stack by means of a CO-tolerant nickel catalyst.

- 5 A prior art example of an SOFC fuel cell system is shown in WO 02/05363 and has an integrated prereformer, afterburner and air preheater unit.

Optimisation of fuel cell system design is desirable to simplify fuel processing, achieve higher levels of component integration, reduce component dimensions
10 and minimise parasitic losses (heat losses, compressor work/pressure drops, etc) in the system. This will not only reduce the capital cost of fuel cell systems but will also result in systems of high electrical efficiency.

Summary of the Invention

- 15 In one aspect, the invention provides an operating cycle for a fuel cell system comprising fuel inlet means, oxidant inlet means, a fuel prereformer, an oxidant preheater, a fuel cell stack, and an afterburner, wherein:
- (a) fuel from the fuel inlet means is prereformed in the prereformer and passed to the anode side of the stack;
 - 20 (b) oxidant from the oxidant inlet means is preheated in the oxidant preheater and passed to the cathode side of the stack where it is reacted with the reformed fuel;
 - (c) a first portion of exhaust from the anode side of the stack is passed to the afterburner and the exhaust from the afterburner is passed to the oxidant
25 preheater to preheat the oxidant;
 - (d) a second portion of exhaust from the anode side of the stack is recirculated to a location upstream of the prereformer for mixing with fresh fuel before the mixture is passed to the prereformer;
 - (e) exhaust from the cathode side of the stack is passed to heat exchanger means
30 associated with the prereformer to preheat the fuel and cool the cathode exhaust gases; and

(f) the cooled cathode exhaust is passed to the afterburner to lower the temperature thereof.

It is particularly advantageous to arrange that the pre-reformer is heated by the exhaust and the cooled exhaust is used to lower the temperature of the afterburner because these measures help to provide a compact and more fuel-efficient system. Use of a pre-reformer to convert at least a proportion of fuel input to the system into hydrogen is advantageous because it allows the system to operate using a variety of fuels.

10

A portion of the exhaust gases from the cathode side of the fuel cell stack is preferably recirculated to a location downstream of the air preheater for mixing with fresh oxidant before the mixture is passed to the cathode side of the stack.

15 In a second aspect, the invention provides an operating cycle for a fuel cell system including a fuel cell stack, wherein fuel is supplied from a fuel prereformer to an anode side of the stack and oxidant is supplied from an oxidant inlet to a cathode side of the stack and the prereformed fuel and the oxidant are reacted in the stack to produce exhausts from the anode and cathode sides of the stack respectively, and wherein a portion of the exhaust from the anode side of the stack is recirculated to be mixed with fuel supplied to the prereformer and a portion of the exhaust from the cathode side of the stack is recirculated to be mixed with oxidant supplied by the oxidant inlet.

25 A portion of exhaust from the anode side of the fuel cell stack is preferably passed to an afterburner and the exhaust from the afterburner is passed to an oxidant preheater to preheat the oxidant. Also, exhaust from the cathode side of the stack is preferably passed to heat exchanger means associated with the prereformer to preheat the fuel and cool the cathode exhaust gases and the cooled cathode exhaust is passed to the afterburner to lower the temperature thereof. The arrangement already mentioned, whereby a portion of the exhaust from the

30

cathode side of the fuel cell stack is recirculated and mixed with fresh oxidant, is advantageous in that it can help to reduce the size of the oxidant preheater.

5 The temperature of the stack may be controlled by varying the temperature of the oxidant that enters the fuel cell stack. This may be accomplished by causing a selectable proportion of the oxidant to bypass the oxidant preheater before entering the stack. Alternatively, or additionally, the temperature of the stack may be controlled by varying the flow rate of oxidant through the stack. This may be accomplished by causing a selectable proportion of the oxidant to bypass
0 the stack and join the exhaust gases from the cathode side of the stack.

We prefer that mixing of recirculated exhaust with fresh reactants be performed by ejector means, with the ejector means driving recirculation of the exhaust. We also maintain the ratio of fuel to recirculated anode exhaust roughly constant
15 in the pre-reformer during normal operation of the system.

Recirculation of a proportion of the exhaust from the anode side of the fuel cell stack and mixing the exhaust with the inlet fuel such that the exhaust to fuel mixture ratio remains substantially constant may also be considered as a further
20 independent aspect of the invention. The exhaust contains steam as a product of the reaction in the fuel cells, therefore an advantage of such an operating cycle is that it removes the need for a separate plant component to generate a supply of steam, thereby increasing the efficiency of the plant.

25 During start-up of the system, the fuel cell stack may be bypassed so that fuel flows directly from the prereformer to the afterburner and is burnt therein with oxidant to preheat at least part of the rest of the system. To further assist the start-up process, the stack may be preheated using electric heating means, the electric heating means comprising a plurality of portions which are
30 independently switchable on and off, the portions being progressively switched off as the stack reaches an operating temperature. During this phase of operation, the fuel cells, or at least the anode sides of the fuel cells, are preferably filled

with an inert fluid such as nitrogen, argon, or helium gas, thereby helping to prevent the anode being oxidised.

We further prefer that isolating valves are provided for selectively isolating at least the anode side of the stack from the upstream and downstream parts of the system, this being particularly useful during scheduled or unscheduled shut-down of the system to allow filling of at least the anode side of the stack with an inert fluid to help prevent unwanted oxidation of the fuel cells.

0 In the preferred embodiment, the fuel cell stack is arranged to have a start up time from cold to power production, of roughly 12 hours. Of course, the skilled person will appreciate that other start up times are possible and it is advantageous to have a start up time of less than twelve hours and roughly any of the following times in hours may be possible: 8, 9, 10, 11, or any time in between
15 these times.

During a hot stand-by operating mode of the system, we arrange that the amounts of reactants passed through the stack are just sufficient to produce an amount of electrical power that (after meeting any parasitic demands of the system) when
20 fed back to electric heating elements associated with the stack, maintains the stack at an operating temperature. Such an arrangement is convenient because it allows the temperature of the system to be maintained, even if the heat produced by the reaction occurring in the fuel cell stack is not sufficient to maintain the temperature of the system on its own.

25

The invention also includes a fuel cell system for performing the above operating cycles. Among other things, the system is preferably provided with a fuel ejector controller to maintain the ratio of anode-side exhaust to fuel in the pre-reformer substantially constant by controlling a bypass valve in a bypass path between the
30 input and the output of the ejector so as to divert a variable amount of fresh fuel through the bypass path, thus varying the ability of the ejector to pull the exhaust from the exit of the anode side of the stack and thereby varying the absolute

amounts of fresh fuel and exhaust which are mixed with each other in the ejector. The fuel ejector controller may be a proportional-integral controller.

5 The system should also include a stack temperature controller for maintaining the temperature of the fuel cell stack by varying the volume of oxidant fed to the cathode, and/or bypassing oxidant around the oxidant preheater, as previously mentioned. The stack temperature controller may also be a proportional-integral controller.

10 All the above aspects are preferably implemented utilising solid oxide fuel cells (SOFC's) in the fuel cell stack.

We prefer that the fuel cells in the SOFC stack comprise anode-supported cells, in which the anode provides structural support for the electrolyte and/or cathode.
15 Anode supported cells have the advantage that it allows an efficient, intermediate temperature operation of the fuel cells to be achieved. Conventionally, planar SOFC cells use the electrolyte as the structural support for the electrodes, which limits minimum electrolyte thickness to around 100 μm . By using a thick, structural anode, much thinner electrolytes can be used with a concomitant
20 reduction in cell resistance. An advantage of the lower cell resistance is the consequent reduction in temperature that may result.

The cost of the SOFC stack is generally a major factor in the overall system cost. Planar stack and cell designs promise the lowest stack production costs since
25 high-volume, low-cost manufacturing processes, such as tape-casting for the cells, may be employed.

Conveniently, the fuel cell stack is arranged to operate in roughly the temperature range of 700-800°C, which is lower than that of conventional
30 electrolyte supported SOFC's which typically operate roughly in the range 800-1000°C. The advantages of lower temperature stack operation are that it may reduce the cost of the stack since it may employ interconnection plates and/or

manifolds made from a ferritic stainless steel, or other low cost metal. It may also reduce the costs of the surrounding balance-of-plant components, such as heat exchangers, piping and afterburners, since they too will not have to be made from high-cost, heat-resistant alloys.

5

The system is preferably arranged such that a shut down mode operates if either or both of the fuel supply to the system and an electricity network to which the system is connected is lost (i.e. fails). The shut down mode is advantageous as it helps to ensure that safe and non-catastrophic shut down is achieved and helps to avoid damage to the system, such as oxidation of the anode, and the like.

10

Conveniently, the system is arranged such that it can accept a supply of natural gas as the fuel input thereto. Preferably, the system is arranged such that it can operate on at least three specified gas compositions with varying sulphur and higher hydrocarbon content. Hence, the system that can readily be provided with a supply of fuel.

15

The system may be arranged such that the amount of electricity generated by the fuel cell stack is controlled by the load demanded from the system. Hence, the amount of fuel supplied to the fuel cell stack is controlled such that the fuel cell stack generates the desired amount of electricity.

20

Brief Description of the Drawings

There now follows by way of example only a detailed description of the present invention with reference to the accompanying drawings of which:

25

Figure 1 shows a schematic of a system with anode gas recycling according to a first embodiment of the present invention;

30

Figure 2 shows a schematic of a system with anode and cathode gas recycling according to a second embodiment of the present invention;

Figure 3 schematically shows a layout for auxiliary (or Balance of Plant) components for a 20kW embodiment of the present invention;

Figure 4 schematically shows a layout for fuel cell stacks in association with the
5 Balance of Plant for the embodiment shown of Figure 1 or 2;

Figure 5 shows a possible external casing for the embodiment of Figure 4;

Figure 6 shows a possible arrangement of an air side heat exchanger for a system
10 with a cathode gas recycle;

Figure 7 shows a possible temperature profile for the heat exchanger of Figure 6
(cold side on the left, hot side on the right);

Figure 8 shows a graph of the calculated power output of the system in kW
15 against time in seconds without cathode recycle during a load-change simulation;

Figure 9 shows a graph of the calculated power output of the system in kW
against time in seconds with cathode recycle during a load-change simulation
20 over the range 100%-50% DC power;

Figure 10 shows a graph of calculated changes in electrical and thermal
efficiencies for a system without cathode gas recycle, for a load-change
simulation over the range 100%-50% DC power;

25

Figure 11 shows a graph of calculated changes in cell voltage and stack current
density for a system without cathode recycle, for a load change simulation over
the range 100%-50% DC power;

Figure 12 shows a plot of system electrical power in kW output/demand during
30 the start-up procedure;

Figure 13 shows calculated current and temperature distributions for a single fuel cell layer in a stack of fuel cell layers comprising a total of 260 anode substrate cells;

- 5 **Figure 14** shows calculated temperature distributions for a single fuel cell layer in a stack of fuel cell layers comprising a total of 65 anode substrate cells at conditions of full and partial electrical loads; and

- Figure 15** shows a schematic exploded view of the components of a single stack layer of a fuel cell stack;
- 10

Detailed Description of the Preferred Embodiments

The main design criteria for the overall system design of the embodiments of the invention detailed here were:

- 15
- Compact (footprint for the packaged unit = 1.6 m x 0.8 m)
 - Potentially low-cost
 - High predicted electrical efficiency (49% at full load, up to 55% at half rated power output).
- 20 The targets were reached by designing a highly integrated system with a high level of internal reforming. Recycling of anode and cathode exhaust gases was integrated into the balance-of-plant (BOP) and enabled significant reductions in heat exchange area and eliminated the need for a separate steam generator for fuel reforming (other than for start-up). Designing for low pressure-drops across
- 25 the entire system minimised the parasitic losses and contributed to the high system efficiency.

- In the example Solid Oxide Fuel Cell (SOFC) system shown in Figure 1, inlet natural gas 2 is mixed with a separate steam supply 7 and passes through a pre-reformer 6 before being fed to the SOFC stack 8, the insulated enclosure or casing of which is indicated by dashed double lines. On an air-side 26 thereof,
- 30

inlet air 10 is preheated in a pre-heater 12 prior to feeding to the stack 8. Exhaust 16 from the cathode or air-side 26 of the stack 8 are then fed back to a heat exchanger H associated with or integrated with the pre-reformer 6, thereby to heat the inlet fuel gas while cooling the exhaust air 16. Thereafter, exhaust 16 is fed to an afterburner 18.

The stack 8 utilises roughly 85% of the fuel fed thereto (which is electrochemically converted to CO₂ and steam) with the remainder being burnt in the afterburner in a conventional manner. Hence, on the anode or fuel side 22 of the stack 8, an amount of the exhaust 14 is fed directly to the afterburner 18. The afterburner 18 exhaust 20 in this system then passes through the air pre-heater 12. Further downstream, residual exhaust heat in the afterburner exhaust 20 is used to generate useful heat for space heating; for example, after the pre-heater 12, the exhaust 20 is passed to a heat recovery heat exchanger 19 to heat water 21 from 40 to 80°C. The exhaust gas is cooled to around 80°C in the process, before being vented to atmosphere at 23.

Further to the above, the system shown in Figure 1 has an anode gas recycle loop, whereby much of the exhaust gas 14 from the anode side 22 of the stack 8 is recycled and mixed with fresh fuel at 24 before the mixture is fed to the pre-reformer 6. The mixing is conveniently performed by an ejector pump 24, which is driven by the fresh fuel 2 and drives the recycling of the anode gas. In this embodiment the fresh fuel comprises desulphurised natural gas, supplied at, e.g., about 3 bar, this pressure being sufficiently high that no compressor work is required to drive the ejector, meaning the energy to drive it is effectively free. However, a fuel gas supply at a lower pressure may require an auxiliary compressor to power the ejector 24. As will be described hereinafter a fuel ejector bypass valve 25 is provided to allow control of the relative proportions of fresh fuel and recycled exhaust gas that are fed to the prereformer 6.

30

The prereformer 6 is provided to reform the higher hydrocarbons in the fuel (the fuel is assumed to contain 6% ethane, and 3% propane, balance methane), and

convert about 25% of the methane. The remaining methane is reformed internally in the stack. The high degree of internal reforming helps to achieve the high predicted system efficiencies illustrated herein, by minimising the requirement for air-cooling of the stack. The reduced air-flow required for cooling the stack reduces the amount of compression which must be performed by the air-blower 28 and this energy saving contributes to the high efficiency.

The prereformer 6 is heated by the air leaving the stack 8 through the recycle loop 17. Due to the action of the stack 8, the anode exhaust 14 contains a proportion (say, at least 25%) of steam. Hence, steam for the reforming reaction is provided by recycling most of the anode exhaust-gas from the stack and mixing it with fresh fuel in the ejector 24. This process also preheats the fresh fuel, and provides some of the heat for the reforming reaction in the prereformer 6. An auxiliary steam generator 7 (e.g., a small flash evaporator) is provided, to provide steam during a system start-up. Likewise, a supply of nitrogen 9 is provided to purge the fuel system, and maintain an inert atmosphere to protect the fuel cell anodes during a heat-up and cool-down of the stack 8 as will be explained hereinafter.

The principal reason for anode gas recycling is to eliminate the need for a large external steam generator, although a small steam supply 7 will still to be required for system start-up. System thermal efficiency is improved, because the heat required to supply the steam would otherwise be extracted from the exhaust gases. Furthermore, capital and running costs are reduced by avoiding the need for an expensive boiler and a supply of de-ionised water. In addition, the heat in the recycled exhaust gas provides much of the preheating required for the fresh fuel 2, reducing the size of, or even eliminating the need for, a fuel pre-heater (not shown). A further potential benefit is that there may be sufficient heat in the recycled anode exhaust 17 to enable a low, but sufficient, degree of pre-reforming (including complete conversion of higher hydrocarbons) to be achieved in a simple adiabatic pre-reformer, instead of the more expensive externally heated pre-reformer 6. A heated pre-reformer 6 may be adopted if

there is insufficient heat for an adiabatic pre-reformer to generate enough heat under part-load operation.

The flow of air 10 carries oxygen to the cathode and also removes excess heat
5 from the stack 8. The flow required for stack cooling is usually larger than the minimum necessary to supply oxygen in the stack 8. However, a large net air-flow should be avoided since it carries a greater proportion of heat out of the system at the final exhaust temperature of 80°C. Additionally, with increasing air flow, a larger fraction of the power generated in the stack 8 is consumed by
10 the air compressor 28 and a larger heat exchange area is required to pre-heat the incoming air within the air pre-heater 12.

The whole system operates at around ambient pressure, so the power demand for compressor 28 is low, since it is merely overcoming the pressure-drop of the
15 plant components. Once compressed, the air is passed through the air preheater 12, which raises its temperature to around 660°C by recovering heat from the exhaust gas. This preheating is necessary to minimise thermal stress on the ceramic components of the stack 8. For the same reason, it is desirable to have a maximum gas temperature rise of 130°C across the stack. In addition, a
20 minimum stoichiometric air ratio λ of 2.0 is desired to avoid cell voltage drops due to oxygen starvation.

The embodiment shown in Figure 1 recycles only a portion of the anode exhaust 17. However, as is shown in Figure 2, embodiments can be realised in
25 which a portion of the cathode exhaust is recycled and thus a second recycle loop is provided. Addition of anode gas recycling to the system significantly increases both the electrical and thermal efficiency of the system, with values of net electrical efficiency as high as roughly 48% at full load.

30 Portions of Figure 2 that are the same as that shown in Figure 1 will not be described further, however, a portion of the cathode exhaust 300 is recycled and an ejector 302 is provided to drive the stream of cathode exhaust gases,

circulation of the exhaust gases around the loop being driven by air 10 entering the system and blown by the blower 28. To control the temperature of the cooling air input to the stack, an air preheater bypass valve 304 is provided so that a portion of the inlet air 10 input to the system can be made to bypass the air preheater 12 using the bypass loop 306. The amount of air fed around the bypass loop 306 is determined by a temperature input to a control algorithm from a thermocouple 308 provided in a region of the ejector 302. It is convenient to use the bypass loop 306 to control the temperature of the air entering the stack 8, thereby controlling the temperature of the stack. The scope for controlling the stack temperature by varying the air flow is limited in this embodiment, since air is supplied at close to minimum stoichiometric air ratio. Thus, the stack temperature is controlled by supplying air at a constant rate and varying its temperature and thus the degree of cooling of the stack.

In the embodiment shown in Figure 2 two waste heat recovery heat exchangers 310,312 have been provided to extract heat from the exhaust of the afterburner 18. Such an arrangement is convenient because in this embodiment the volume of exhaust gases is much lower on part load and such an arrangement allows one of the heat exchangers 310,312 to be bypassed when the system is being run at partial load, when a smaller exchange area is sufficient.

Referring to Figure 2, recycling a proportion of the hot cathode exhaust reduces both the fresh air flow and the amount of heat that must be transferred in the air pre-heater 12. This allows a significantly smaller air pre-heater 12 to be specified with a corresponding cost saving. The penalty is that, although fresh air flow is reduced, the ejector is pressure-driven, so additional power is required to drive the compressor. The main benefit of designing the system with cathode gas recycle is an increase in thermal efficiency and system compactness.

As shown in Figure 2, a suitable balance-of-plant (BOP) system may include recycling of both the anode and cathode exhaust gases. The BOP layout for such a system is shown schematically in Figure 3, illustrating the pipes and ducts

necessary to interconnect the major components. The design of the system BOP focuses on the major cost and size elements which are the heat exchangers 12, 310, 312, pre-reformer 6, afterburner 18 and compressor(s) 28, since a reduction in size of these components will contribute not only to major cost reductions but also to a more compact packaged system. The complete system is illustrated schematically in Figure 4, where it is separated into three main sections: the stack module 400, the BOP module 402 and the control and power conditioning module 404. A photo-rendered picture of the packaged unit is shown in Figure 5. The system is designed for siting indoors, with a key objective therefore being to make it compact. The unit designed has a total footprint of $1.6 \text{ m} \times 0.8 \text{ m} = 1.3 \text{ m}^2$. Heat exchangers and the pre-reformer were designed for durable and stable operation, and are therefore conservatively oversized in the concept shown with respect to the number of plates and plate spacing. The BOP module and the stack module are insulated to minimise heat losses by means of a 100 mm layer of high performance, microporous insulation; total heat loss with this configuration was calculated to be 835 W at the nominal full electrical power output of 20 kW. The criterion for the sizing of the pipework was that the gas velocity was generally kept below 20 m/s to avoid unnecessary pressure drops.

The heat exchangers are of plate type with dimensions 500 mm x 200 mm and a thickness of 1 mm. For the case with no cathode gas recycle (i.e., as shown in Figure 1), the heat exchange is 380 W per plate, requiring a total of 120 plates with a total area of 12 m^2 (9.6 m^2 net). For the system with cathode gas recycle (i.e. Figure 2), because of the higher temperature difference between the streams and the significantly lower flow, the heat exchange is 1.3 kW per plate. This requires a total of 3 plates with a total area of 0.3 m^2 . This reduction in size, and therefore cost, of the air pre-heater is an advantage of employing a cathode gas recycle loop. A photo-rendered impression of the smaller heat exchanger is shown in Figure 6 and the calculated temperature distribution across a heat exchanger plate is shown in Figure 7.

Both embodiments (i.e. with or without cathode gas recycle) are provided with control loops, which relate the fuel supply to the applied stack current, and regulate the anode gas recycle loop and control the stack temperature. The control loops are generally PI (proportional-integral) controllers (although, as the skilled person will appreciate, other control strategies are equally possible), with a supervisory PLC controller which modifies their set-points according to the required power output. The stack temperature is regulated by changes, either to the temperature or flow, of the air supply.

- 10 Considerations in the control of this embodiment of the system are as follows:
- maintain constant stack temperature from 50 to 100% rated power
 - fuel utilisation to remain constant at all power outputs
 - oxygen / carbon (in the fuel) ratio at the pre-reformer inlet always to exceed 1.8 in order to avoid the potential for carbon deposition
 - 15 • water temperature to remain constant at 80°C
 - exhaust temperature not to fall below 50°C
 - oxygen (in air) / fuel ratio, lambda, at the stack inlet always to exceed 2.0

Whether or not a cathode gas recycle loop is provided, it is possible to meet these objectives, although the method for stack temperature control differs. However, the stack temperature is controllable to within a few degrees over the range 30-100% power by regulation of the air supply. This is largely as a result of the high thermal mass of the stack, which means that any temperature changes occur slowly.

25 The dynamic performance of a planar SOFC system is predicted to be significantly better than a tubular type system since, in this planar design, the stack is much more compact, and therefore has a smaller inventory of reactants. In addition, the thermal conductivity of the metallic, planar stack components is much higher than the ceramic components of a tubular stack, which should help 30 to prevent large temperature gradients occurring within the stack. Simulations

have also been performed on a system cold start, and to this end additional plant items (a steam generator, an external heat supply to the stack and various bypass valves) have been provided. Further simulations have also been performed to investigate the control and component requirements for putting the system into
5 'hot standby'. Hot stand-by is important, for example, during a temporary loss of the mains supply, since it would avoid the need for a complete shut-down of the system and would allow it to re-start exporting power with only a short interruption.

10 Typical predicted results are illustrated in Figures 8 to 12. Figures 8 and 9 show the predicted electrical and thermal power outputs of the planar SOFC systems without and then with cathode gas recycle, during a simulation where the load was reduced in steps from 100% to 50% DC power. It can be seen that the electrical power output is predicted to closely follow changes in current. This is
15 largely because the control enables the stack to be maintained at a constant temperature, as discussed earlier. The thermal power output is shown to take longer to react to load changes. It can also be seen from Figure 9 that the thermal power output of the system with cathode recycle is somewhat higher than that without recycle, since less heat is rejected in the exhaust. Figure 10 shows
20 the changes in electrical and thermal efficiencies with reduced power output. Down to 50% of rated power output, electrical efficiency is seen to rise as a result of the lower losses when operating the stack at lower current density and, therefore, higher voltage (see Figure 11). Figure 12 shows the results of a start-up simulation.

25 Stack modelling was performed for a 20KW module of 260 anode substrate cells 20cm x 20cm, based on the SOFC stack 8 concept using anode-supported thin electrolyte layer cells. Although the skilled person will appreciate that many different designs of SOFC stack 8 are possible, one possible example is
30 described further below. Figure 13A shows the resulting current density distribution and Figure 13B the temperature distribution in one layer of this stack, while Table 1 below is a summary of the main results of the calculations.

TABLE 1

Temperatures		Energy balance/per cell	
	°C		W
Fuel inlet	700	electric power output	73.5
Air inlet	700	heat transfer by air	23.0
5 Fuel outlet	731	heat transfer by fuel	1.3
Air outlet	782	heat transfer by radiation	13.9
Maximum	800		
Electrical efficiency		Pressure Loss	
	%		mbar
related to converted fuel	65	in air channels	6
10 related to input fuel	43	in fuel channels	<1
Operation parameters		Fuel gas composition	
Fuel utilisation	70%	in	out
Air stoichiometry	6 mol/mol	mol%	mol%
Current density	300 mA/cm ²	H ₂	28.63 18.58
15 Cell voltage	679 mV	CO	1.99 3.10
Power density	204 mW/cm ²	CO ₂	5.31 15.00
		CH ₄	17.10 0.13
		H ₂ O	46.97 63.19
		N ₂	0.00 0.00

20

The stack 8 was assumed to be operated on 30% pre-reformed methane fuel, i.e. 70% of the methane is internally reformed, with air and fuel inlet temperatures of 700°C. For a fuel utilisation of 70%, the stack attained an average power density of 0.21 W/cm², where the maximum temperature did not exceed 800°C. This 20 kW SOFC module comprised several smaller stacks rather than a single large stack.

The smaller stacks may be arranged in different ways, for example they may be arranged in parallel and/or in series. One of these options was a so-called cascade of stacks. In the cascade, the fuel flows through a series of stacks: the exhaust fuel from two stacks in one stage is combined and fed to one single stack in the next stage. Fresh air is supplied in parallel to all stacks in all stages. An advantage of this arrangement is that, while the fuel utilisation in each successive member of the series of stacks in the cascade remains low, the overall fuel utilisation still can reach values above 60%. However, the overall power output of the cascade arrangement was not substantially increased in comparison with a single stack operating under the same conditions.

35

Similar results were obtained for another option where both air and fuel flowed through a series of stacks. This latter arrangement also showed the disadvantage of high temperature air being fed into stacks in the next stage, because it raises the temperature levels to undesirably high values. Moreover, the series connection of gas flows leads to higher pressure drops, which would require more work by the compressors, leading to higher electrical power losses in the system. For these reasons, it was decided to make the arrangement for the 20 kW module (260 cells) with four stacks of 5 kW each, which are all fed with air and fuel in parallel.

Additional modelling of a 5 kW stack (65 cells) was performed, in particular at partial load levels. This 5 kW stack was design to contain 65 cells of 20 cm x 20 cm each (effective electrode area $19 \times 19 = 361 \text{ cm}^2$).

For these calculations, the natural gas fuel composition exiting the adiabatic pre-reformer (derived from the process flow modelling) was taken as input for the stack at a temperature of 650°C. Air inlet temperature was also 650°C. The results of the calculations are shown in Table 2 below.

TABLE 2

Electric load	%	100	75		50		25	
Air stoichiometry (stack, 100% conversion)		3.7	3.7	3.2	3.7	2.7	3.7	2.0
Maximum stack operating temperature	°C	809	793	803	769	789	739	764
Minimum stack operating temperature	°C	722	727	741	728	743	718	738
Maximum temperature Gradient	K/mm	1.08	0.97	1.02	0.78	0.83	0.46	0.49
Air temperature increase in the stack	°C	111	98	103	81	95	69	89
Fuel temperature increase in the stack	°C	73	77	91	78	103	71	101

In the first series of calculations at electric loads of 100%, 75%, 50%, and 25%, the air stoichiometry was kept constant at a value of 3.7, in the second series of

calculations at the same loads, the stoichiometry was gradually lowered with decreasing load, but kept at or above the minimum value of 2.0. The results indicated that the minimum stack temperature was always in the range of 720 to 740°C, more or less independent of the load and the air stoichiometry. The maximum stack operating temperature was close to 800 °C at full and three-quarters load, but at 50% partial load and 25% partial load, the cooling effect of the air flow was evident.

Figure 15 exemplifies the design of an SOFC stack layer used to achieve the results detailed above. This is an internal manifold design, which enables a parallel fuel and air flow configuration (either counter-flow or a co-flow). Temperature distributions across the cells are more symmetrical and temperature gradients are lower in this layout.

In the counter-flow arrangement, air and fuel gases enter via the base plate 1700 of the stack through the two outer tube sections 1702, 1704. In each stack layer, gases enter an enclosed plenum 1706 and are then distributed across the entire surface of the anode 1712 or cathode 1710 of the single cell before flowing to the exhaust plenum 1708 from where the gases exit the stack via the central pipe section. The anode 1712 and cathode 1708 facing sides of the interconnect plate are identical. In this arrangement, the cathode 1710 is provided as thin (5µm) layer on top of an electrolyte 1714 separating it from the anode 1712. The thinness of the cathode reduces the resistance of the cell and thus reduces the temperature required to run the stack 8. Reduction of the stack temperature has consequential advantages in the surrounding plant and should reduce the heat tolerance of components such as heat exchangers, piping and afterburners, since they too will not have to be made from high-cost, heat-resistant alloys.

A 20 cm x 20 cm cell size underwent a series of tests. For example, a test was performed with a 10-cell stack. At an operation temperature of 800°C this stack gave a power output of 1.6 kW (220 A @ 7.30 V; i.e. 0.61 A/cm² and 0.44 W/cm²) with humidified hydrogen at a fuel utilisation of 44%. At 880°C the

power output was 2.4 kW (340 A @ 7.14 V; i.e. 0.94 A/cm² and 0.68 W/cm²) at a similar fuel utilisation of 47%. Performance of this stack design has also been demonstrated on methane. The results demonstrate that the stack design can meet performance requirements for the system with internal reforming.

5

The embodiments described above can be started from cold, an important aspect for any practical system. A hot standby mode has also been demonstrated. It was shown that a system with cathode recycle gives a more efficient and compact overall system but the control is more complex. A design for the power conversion was developed that allows for the particular attributes of the SOFC and meets the requirements for connecting the SOFC system to the PEC. Further noteworthy aspects of the system described herein are as follows:

- The system operates on pipeline natural gas (NG).
- 15 • The system generates electricity to feed into a power grid
- The system has a target net electrical efficiency (AC output, based on LHV of fuel) of at least 45% at full power.
- The system has a target overall efficiency of at least 75% (AC power and heat, based on LHV of fuel) at full power.
- 20 • The SOFC stack has a nominal operating temperature of 780°C at full power (note this is substantially lower than SOFC systems based on known electrolyte supported cells).
- The system is capable of a turn-down to 50% or less of its rated power output.
- The system is simple and compact, to minimise the capital cost.

25

As discussed above, and as far as possible, the following parameters are used to control the system:

- the average stack temperature remains roughly constant, and in particular across the 100-50% rated power operating range.
- 30 • fuel utilisation to remain roughly constant at all power outputs.

- oxygen/carbon ratio at the pre-reformer 6 inlet to substantially always exceed 1.8, in order to avoid carbon deposition.
 - water temperature to remain roughly constant at 80°C.
 - exhaust temperature not to fall below roughly 50°C.
- 5 • stoichiometric air ratio (λ , lambda) to substantially always exceed 2.0.

In this system, the stack temperature control is provided by varying λ , by varying the power output of the air compressor. A temperature sensor 102 is provided in the stack (the stack temperature may also be taken as the average reading of
10 several thermocouples placed at different locations within it). This provides the input to a stack temperature controller, a PI controller. The bias (default control signal) of this controller is provided by a master stack controller, which sets the fuel and air flows proportional to the stack current. For example if the current is halved, then the default air flow would be halved, and then the temperature
15 controller then controls around this default air flow. The PI temperature controller is set to clip at $\lambda = 2.0$; this minimum signal is also set by the master stack controller.

The fuel supply is controlled proportional to the stack current by the master stack
20 controller, to maintain a constant fuel utilisation. For the purposes of this system, it is assumed that the fuel is available at 3 bar, and therefore the flow can be controlled by a throttle valve and flow meter. Should this not be the case, a variable power compressor would be provided to drive the fresh fuel supply.

25 Maintaining an oxygen/carbon (O/C) ratio of at least 1.8 at the pre-reformer inlet (important for the prevention of carbon formation), is largely a problem of controlling the anode recycle loop at part-load. Ejectors generally have a highly non-linear part-load characteristic. At a constant recycle ratio, the pressure rise is proportional to the square of the driver flow. Since the pressure drop of the
30 components within the recycle loop is nearer to directly proportional to the flow,

then this implies that with an uncontrolled ejector the recycle ratio will fall at part-load.

This presents a design problem, since the O/C ratio is proportional to the recycle ratio. It is not desirable to exceed an O/C ratio of about 2.0, since if more exhaust gas is recycled than necessary it affects the stack voltage by reducing the fuel partial pressure.

However, if the ejector is sized to maintain an O/C ratio of around 2.0 at full power, then even a relatively small reduction in power output will result in the O/C ratio falling below 1.8.

The solution adopted here is to use an oversized ejector (one which would drive a recycle ratio of greater than that required to maintain the desired O/C ratio if all the gas were passed through it at full load), and bypass it. Thus, some of the fresh fuel is diverted around the ejector, through a bypass channel controlled by the fuel ejector bypass valve 25. The fuel by passing the ejector 24 is mixed with the other gases downstream of the ejector 24. The bypass valve 25 is controlled by a PI controller, taking its input signal from a flow-meter 100 in the recycle loop 17.

In order to control the water temperature, another PI controller is provided which controls the water flow through the heat-recovery heat exchanger 19, with a temperature sensor in the water outlet. The PI controller controls a flow valve 104 and also has an input from a temperature sensor 106.

An air bypass valve 110 allows the stack to be bypassed by air, and is closed during normal operation forcing the air to enter the stack 8. A stack fuel bypass valve 108 is also provided and allows fuel to bypass the stack 8. Again, in normal operation the fuel stack bypass valve is closed so that fuel enters the stack 8. The bypass valves are used in conjunction with a stack fuel isolating valve 112 and a stack air isolating valve 114. The two pairs of valves (the stack

fuel bypass valve 108, stack fuel isolation valve 112; and stack air bypass valve 110, stack air isolation valve 114) work in conjunction so that when one valve of each pair is open the other is closed and visa versa.

5 In order to control the system so far described, the following strategy is utilised. Firstly, the system must be started from cold and in such a situation it is assumed that the stack is heated from ambient temperature to its normal operating temperature by electric windings in its housing (not shown), and therefore a power supply is required during start-up. A start-up time from completely cold
10 of 6-12 hours is typical.

During the cold start procedure, the stack is initially isolated, with fuel and air bypassed around it, and fed directly to the afterburner. The stack is filled with nitrogen on the anode side (or a 5% hydrogen in nitrogen mixture) at this stage,
15 to protect the anodes. The inert mixture surrounding the anodes prevents oxidation of the catalyst, which is likely to destroy the catalyst.

The heat from the afterburner is used to heat the BOP components (particularly the pre-reformer 6) up to a temperature where they can operate normally. During
20 this initial phase, the steam generator 7 is switched on, and supplies the steam required for the reforming reaction (and also some extra heat for the pre-reformer 6). An extra controller is provided, which manipulates the air flow to maintain a constant afterburner exhaust temperature of 850°C, thus avoiding overheating any components.

25 The procedure adopted for starting the system with a warm stack and a cold balance of plant, is as follows.

System started. Fuel is fed at around 25% of the fuel rate of full power. The
30 steam generator 7 is switched on, which generates enough steam to maintain an O/C ratio of 2.2. Air is fed, with the burner temperature controller manipulating the air flow to maintain an afterburner temperature of 850°C. The anode recycle

controller is switched on, as is the water temperature controller. The normal stack temperature controller is off. The system is left in this state for 10 minutes to warm up.

- 5 After 10 minutes, the fuel and air are diverted back into the stack, which is switched on with a current of 30 A. The normal fuel and air control loops are switched on, but with a fuel utilisation of 80% to increase the heat input. The electrical heat input to the stack is increased to increase the demand for cooling, and thus increase the heating effect of the air in the pre-reformer. The system is
10 left in this state for 1 minute. At this point, the system is self-sustaining, in that it does not need an external power supply.

The stack current is increased to 47 A (50% full power). The system is allowed to run for a further minute.

15

The external steam supply is switched off. The system is allowed to run for five minutes.

- The stack current is increased to 70 A. The system is allowed to run until the
20 pre-reformer metal temperature has reached 600°C.

The electric heating to the stack housing is switched off and the fuel utilisation is increased to the normal 85%. The system is allowed to run for 5 minutes.

- 25 The stack current is increased to 90 A. The system is allowed to run for five minutes.

The stack current is increased to 108 A (full power), and allowed to run.

- 30 This gives a total start-up time from hot standby to full power of 47 minutes. However, for all but 10 of those minutes the system is generating more power than it is using. It could be possible to reach full power sooner than this; five

minute gaps were allowed between power increases to minimise thermal stress on the stack. The actual heat-up time depends upon the rate of heat transfer from the gas to the metal, which is difficult to estimate. It is likely to be rapid initially, due to the large temperature difference between the two. However, this
5 would imply that most of the available heat was absorbed by the afterburner and its associated pipework, cooling the gases to near ambient temperature (and probably causing internal condensation).

CLAIMS

1. An operating cycle for a fuel cell system comprising fuel inlet means (2), oxidant inlet means (10), a fuel prereformer (6), an oxidant preheater (12), a fuel cell stack (8), and an afterburner (18), wherein:
 - 5 (a) fuel from the fuel inlet means (2) is prereformed in the prereformer (6) and passed to the anode side (22) of the stack;
 - (b) oxidant from the oxidant inlet means (10) is preheated in the oxidant preheater (12) and passed to the cathode side (26) of the stack where it is reacted with the reformed fuel;
 - 10 (c) a first portion of exhaust (14) from the anode side (22) of the stack is passed to the afterburner (18) and the exhaust from the afterburner is passed to the oxidant preheater (12) to preheat the oxidant;
 - (d) a second portion (17) of exhaust from the anode side of the stack is recirculated to a location (24) upstream of the prereformer (6) for mixing
15 with fresh fuel before the mixture is passed to the prereformer (6);
 - (e) exhaust from the cathode side (26) of the stack is passed to heat exchanger means (H) associated with the prereformer (6) to preheat the fuel and cool the cathode exhaust gases; and
 - (f) the cooled cathode exhaust is passed to the afterburner (18) to lower the
20 temperature thereof.
2. An operating cycle according to claim 1, wherein a portion of the exhaust gases from the cathode side (26) of the stack is recirculated to a location (302) downstream of the air preheater (12) for mixing with fresh oxidant before the mixture is passed to the cathode side of the stack.
- 25 3. An operating cycle for a fuel cell system including a fuel cell stack (8), wherein fuel is supplied from a fuel prereformer (6) to an anode side (22) of the stack and oxidant is supplied from an oxidant inlet (10) to a cathode side (26) of the stack and the prereformed fuel and the oxidant are reacted in the stack to produce exhausts (14, 16) from the anode and cathode sides of the stack
30 respectively, and wherein a portion of the exhaust (14) from the anode side (22) of the stack is recirculated to be mixed with fuel supplied to the prereformer (6)

and a portion of the exhaust from the cathode side (26) of the stack is recirculated to be mixed with oxidant supplied by the oxidant inlet (10).

4. An operating cycle according to claim 3, wherein a portion of exhaust (14) from the anode side (22) of the stack is passed to an afterburner (18) and the exhaust from the afterburner is passed to an oxidant preheater (12) to preheat the oxidant.
5. An operating cycle according to claim 3 or claim 4, wherein exhaust from the cathode side (26) of the stack is passed to heat exchanger means (H) associated with the prereformer (6) to preheat the fuel and cool the cathode exhaust gases and the cooled cathode exhaust is passed to the afterburner (18) to lower the temperature thereof.
6. An operating cycle according to any preceding claim, wherein the temperature of the stack is controlled by varying the temperature of the oxidant that enters the stack.
- 15 7. An operating cycle according to claim 6 as dependent on any one of claims 1, 2, 4 or 5, wherein the temperature of the oxidant that enters the stack is varied by causing a selectable proportion of the oxidant to bypass the oxidant preheater before entering the stack.
- 20 8. An operating cycle according to any preceding claim, wherein the temperature of the stack is controlled by varying the flow rate of oxidant through the stack.
9. An operating cycle according to claim 8, wherein the flow rate of oxidant through the stack is varied by causing a selectable proportion of the oxidant to bypass the stack and join the exhaust gases from the cathode side (26) of the stack.
- 25 10. An operating cycle according to any preceding claim, wherein mixing of recirculated exhaust with reactants is performed by ejector means (24, 302), the ejector means driving recirculation of the exhaust.

11. An operating cycle according to any preceding claim, wherein a ratio of fuel to recirculated anode exhaust is maintained roughly constant in the pre-reformer during normal operation of the system.
12. An operating cycle according to any preceding claim, wherein during
5 start-up of the system the fuel cell stack is preheated using electric heating means, the electric heating means comprising a plurality of portions which are independently switchable on and off, the portions being progressively switched off as the stack reaches an operating temperature.
13. An operating cycle according to any preceding claim, wherein during
10 start-up of the system the fuel cell stack (8) is bypassed so that fuel flows directly from the prereformer (6) to the afterburner (18) and is burnt therein with oxidant to preheat at least part of the rest of the system.
14. An operating cycle according to any preceding claim, wherein during a
15 hot stand-by operating mode of the system, the amounts of reactants passed through the stack are just sufficient to produce an amount of power that when fed back to electric heating elements associated with the stack, maintains the stack at an operating temperature.
15. A fuel cell system comprising:
- (a) fuel inlet means (2);
 - 20 (b) oxidant inlet means (10);
 - (c) an stack (8) having an anode side and a cathode side;
 - (d) a fuel prereformer (6) for receiving fuel from the fuel inlet means (2), reforming it and to passing it to the anode side (22) of the stack;
 - (e) an oxidant preheater (12) for receiving oxidant from the oxidant inlet means
25 (10), preheating it, and passing it to the cathode side (26) of the stack for reaction with the reformed fuel;
 - (f) an afterburner (18) for receiving a first portion of exhaust (14) from the anode side (22) of the stack, burning it with additional oxidant, and passing the exhaust to the oxidant preheater (12) to preheat the oxidant;

(g) a mixing device (24) located upstream of the prereformer (6) for receiving a second portion (17) of exhaust from the anode side of the stack, mixing it with fresh fuel and passing the mixture to the prereformer (6);

5 (h) heat exchanger means (H) associated with the prereformer (6) for receiving exhaust from the cathode side (26) of the stack to preheat the fuel, cool the cathode exhaust gases and pass the exhaust to the afterburner (18) to lower the temperature thereof.

16. A fuel cell system according to claim 15, wherein a mixing device (302) is located downstream of the air preheater (12) for receiving a recirculated portion
10 of the exhaust gases from the cathode side (26) of the stack, mixing the exhaust gases with fresh oxidant, and passing the mixture to the cathode side of the stack.

17. A fuel cell system comprising:

(a) a fuel cell stack (8), having an anode side (22) and a cathode side (26);

15 (b) a fuel prereformer (6) for supplying prereformed fuel to the anode side (22) of the stack;

(c) an oxidant inlet (10) for supplying oxidant to the cathode side (26) of the stack;

(d) a fuel mixing device (24) located upstream of the prereformer and an anode side recirculation loop (17) for recirculating a portion of the exhaust (14) from the anode side (22) of the stack to the fuel mixing
20 device, whereby the mixing device mixes the exhaust with fresh fuel and passes the mixture to the prereformer;

(e) an oxidant mixing device (24) located upstream of the cathode side of the stack and a cathode side recirculation loop (300) for recirculating a
25 portion of the exhaust from the cathode side (26) of the stack to the oxidant mixing device, whereby the oxidant mixing device mixes the exhaust with fresh oxidant and passes the mixture to the cathode side of the stack.

18. A fuel cell system according to claim 17, wherein an afterburner (18)
30 receives a portion of the exhaust (14) from the anode side (22) of the stack, burns

it with extra oxidant, and passes its exhaust to an oxidant preheater (12) to preheat the oxidant.

19. A fuel cell system according to claim 17 or claim 18, wherein heat exchanger means (H) associated with the prereformer (6) receives exhaust from the cathode side (26) of the stack thereby to preheat the fuel and cool the cathode exhaust gases and then passes the cooled cathode exhaust to the afterburner (18) to lower the temperature thereof.

20. A fuel cell system according to any one of claims 15, 16, 18 or 19, wherein a bypass path (306) is provided to allow a selectable proportion of the oxidant to bypass the oxidant preheater (12), the proportion of oxidant to be bypassed being selected by valve means (304), whereby the temperature of the oxidant that enters the stack is varied and the temperature of the stack is controlled.

21. A fuel cell system according to any one of claims 15 to 20, wherein a bypass path is provided to allow a selectable proportion of the oxidant to bypass the stack (8), the proportion of oxidant to be bypassed being selected by valve means (110), whereby the flow rate of the oxidant that enters the stack is varied and the temperature of the stack is controlled.

22. A fuel cell system according to any one of claims 15 to 21, comprising ejector means (24, 302) for mixing recirculated exhaust with reactants and driving recirculation of the exhaust.

23. A fuel cell system according to any one of claims 15 to 22, wherein electric heating means associated with the stack comprises a plurality of portions which are independently switchable on and off, and control means for switching the portions on at start-up of the system to preheat the stack and progressively switching off the portions as the stack reaches an operating temperature.

24. A fuel cell system according to any one of claims 15 to 23, wherein a bypass path is provided to allow fuel to bypass the stack (8) during start-up of the system under control of valve means (108) in the bypass path, fuel from the

bypass path being delivered to the afterburner (18) for burning therein with oxidant to preheat at least part of the rest of the system.

25. A fuel cell system according to any one of claims 15 to 24, wherein bypass paths are provided to allow fuel and oxidant to bypass the stack (8) during a hot stand-by operating mode of the system under control of valve means (108, 110) in the bypass paths, and control means for controlling the valves such that the amounts of reactants passed through the stack are just sufficient to produce an amount of power that when fed back to electric heating elements associated with the stack, maintains the stack at an operating temperature.

10 26. A fuel cell system according to any one of claims 15 to 25, wherein the fuel cells comprises anode-supported cells, in which the anode provides structural support for the electrolyte and/or cathode.

27. A fuel cell system according to any one of claims 15 to 26, wherein isolating valves (112, 114) are provided for selectively isolating the stack from the fuel prereformer and the oxidant preheater.

15 28. A fuel cell system according to any one of claims 15 to 27, wherein the fuel cells are of the solid oxide type.

29. An operating cycle for a solid oxide fuel cell system according to any one of claims 1 to 14.

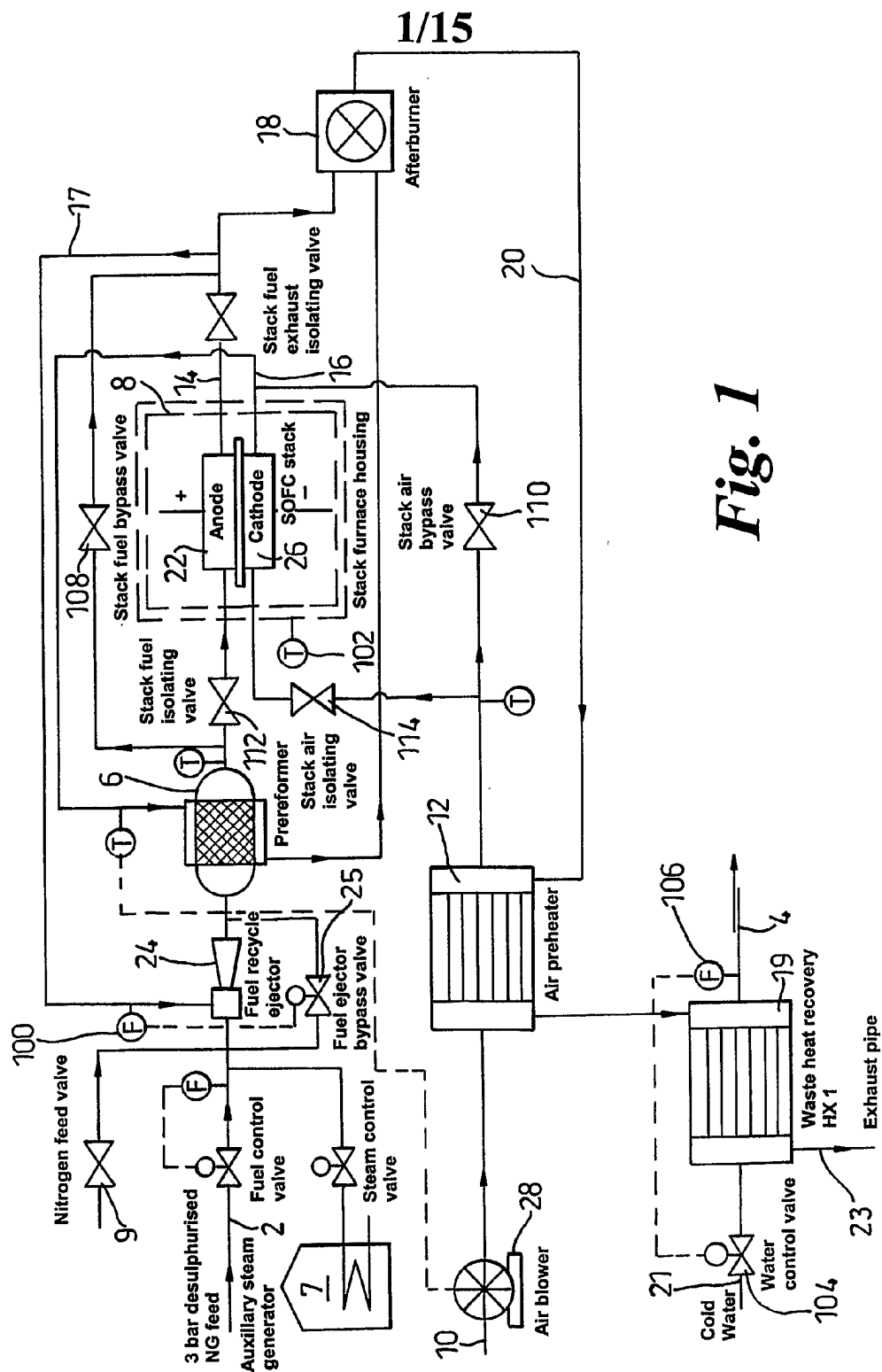


Fig. 1

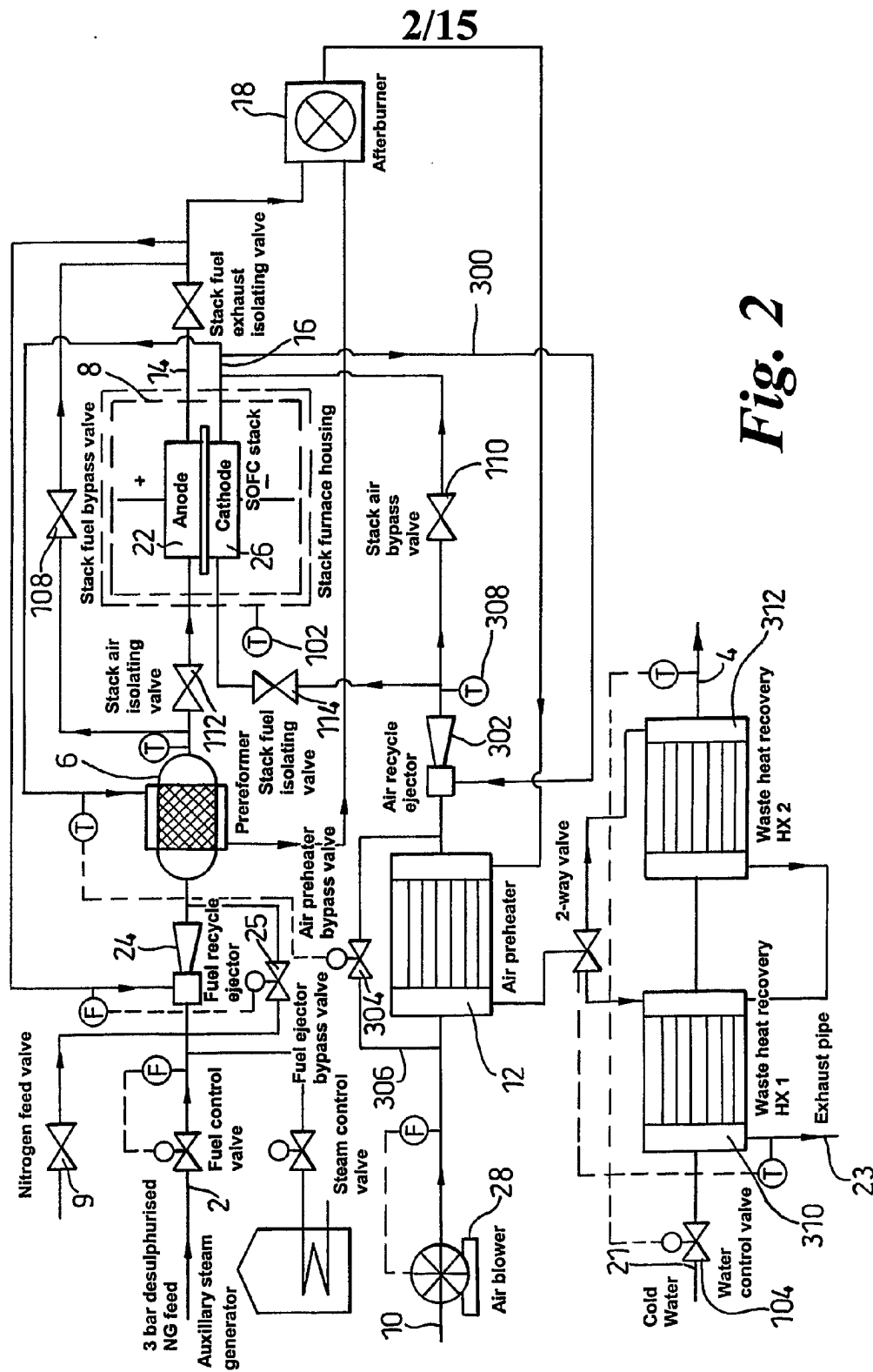


Fig. 2

3/15

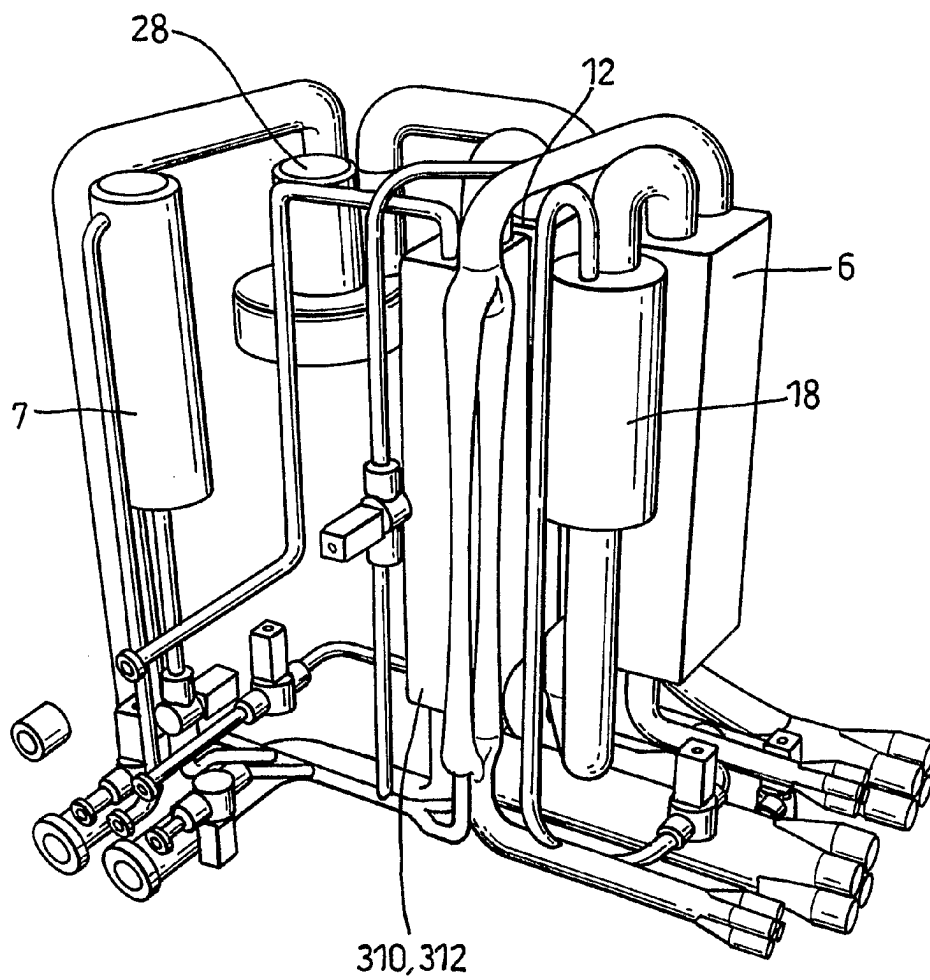


Fig. 3

4/15

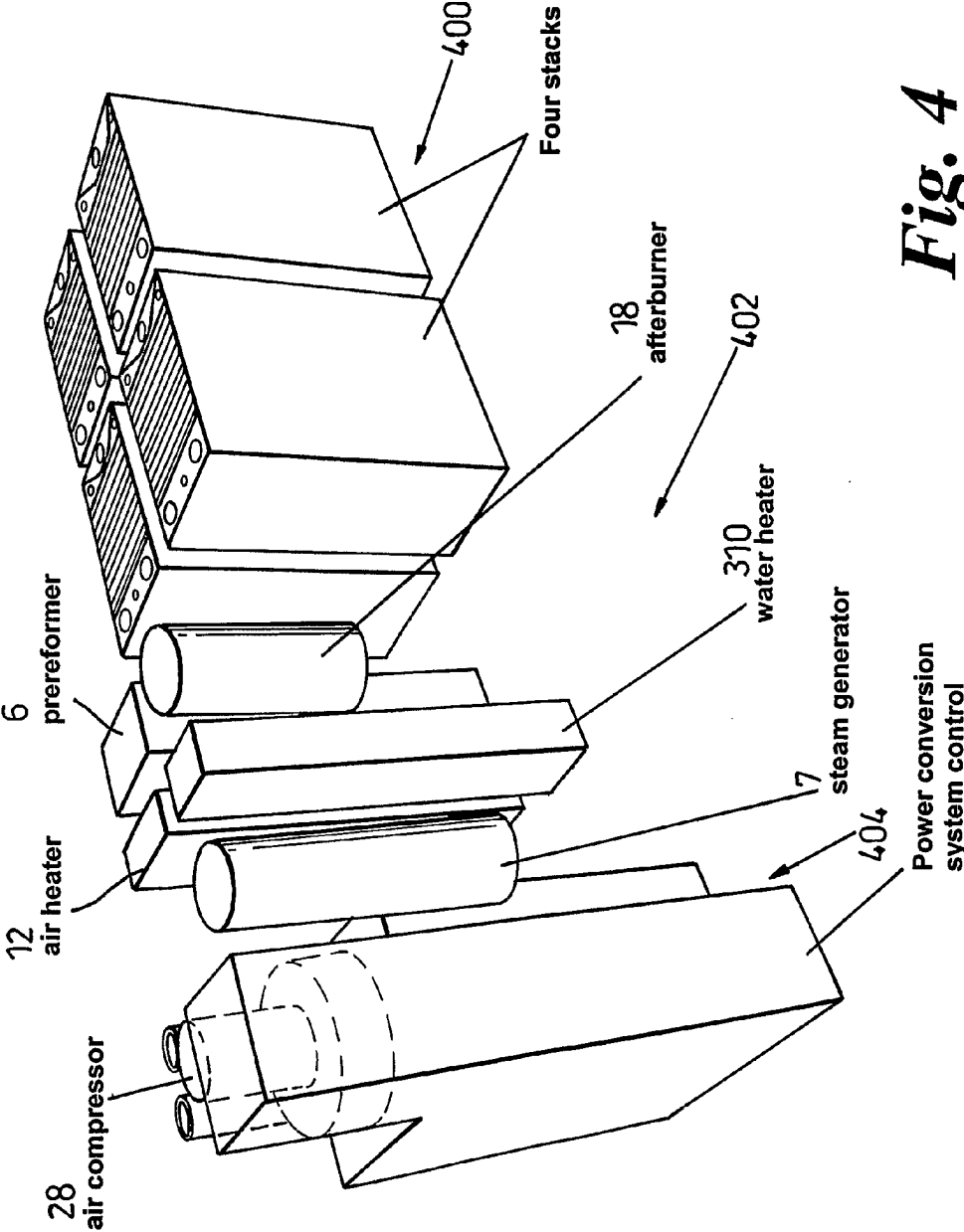


Fig. 4

5/15

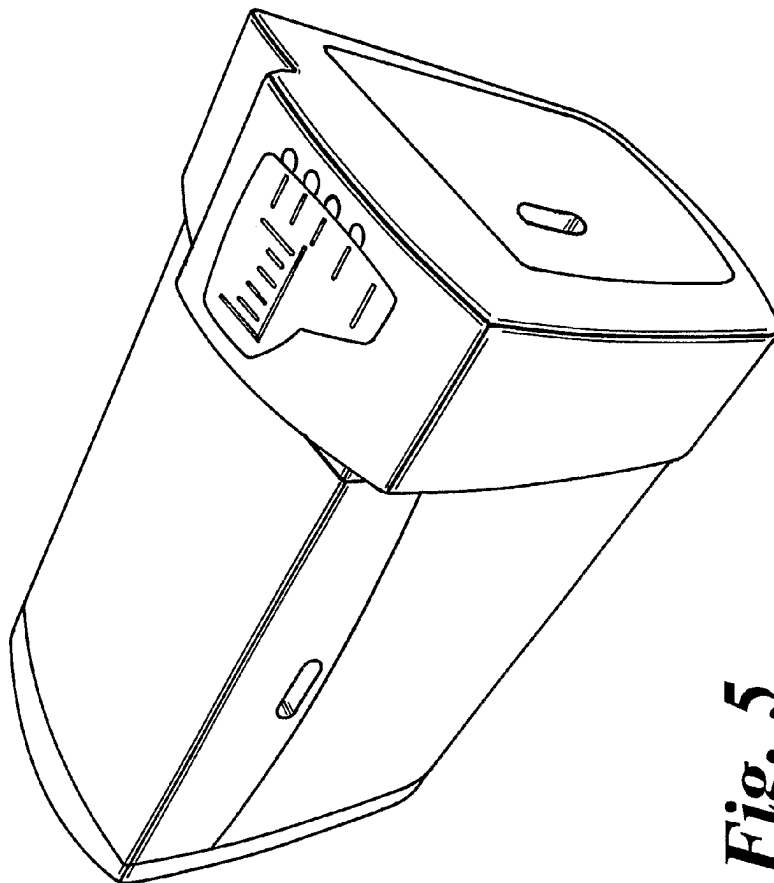


Fig. 5

6/15

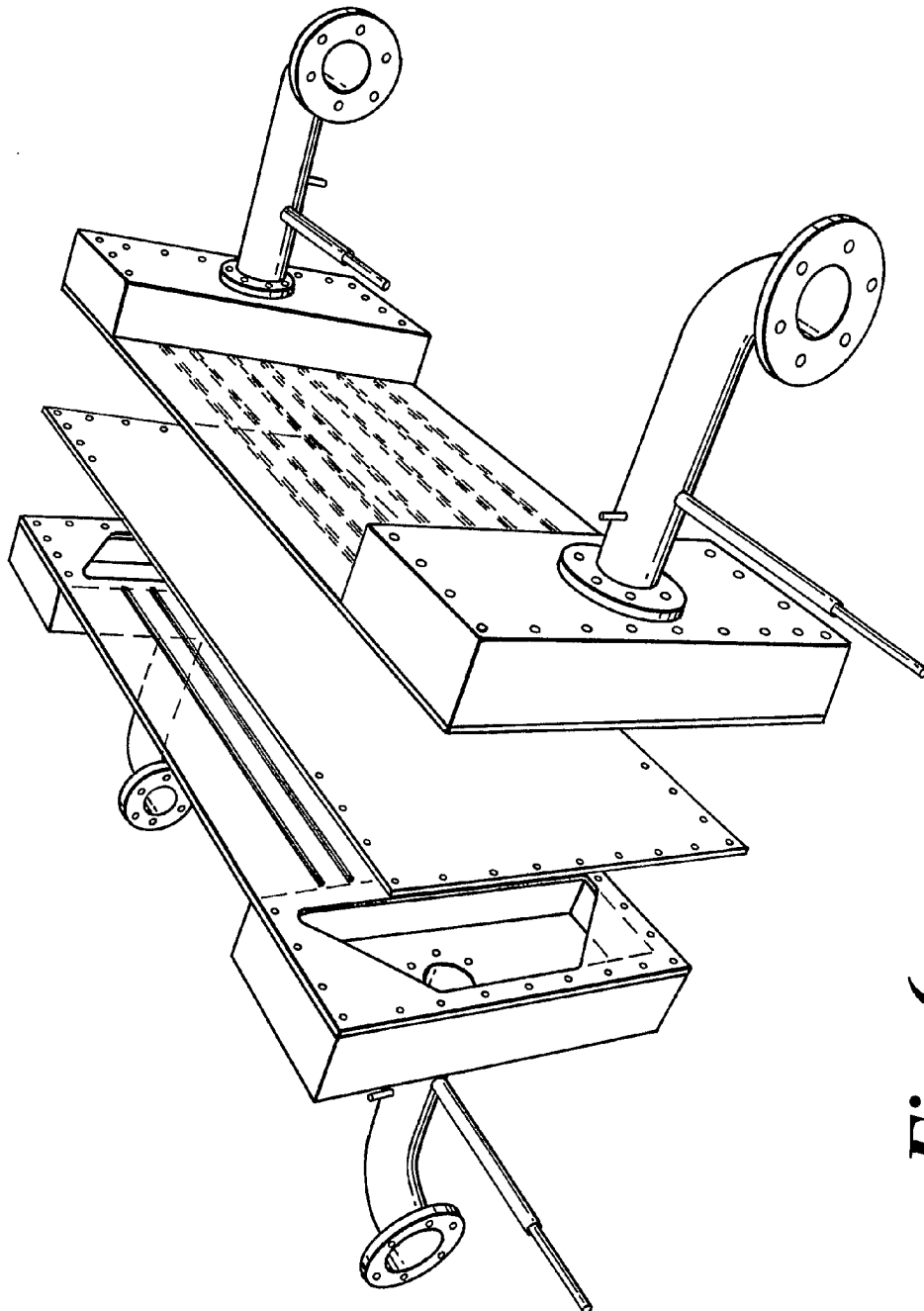
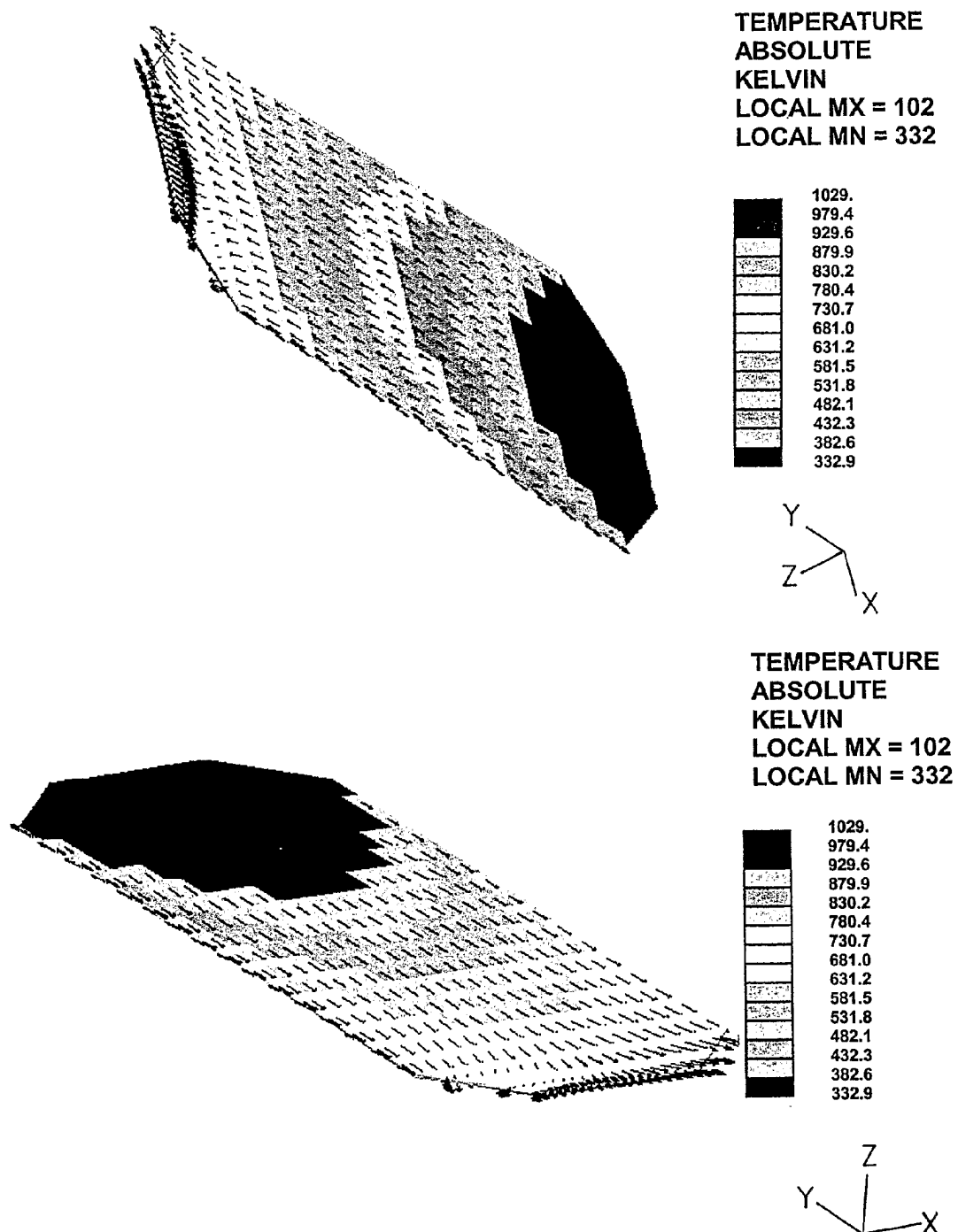


Fig. 6

7/15

*Fig. 7*

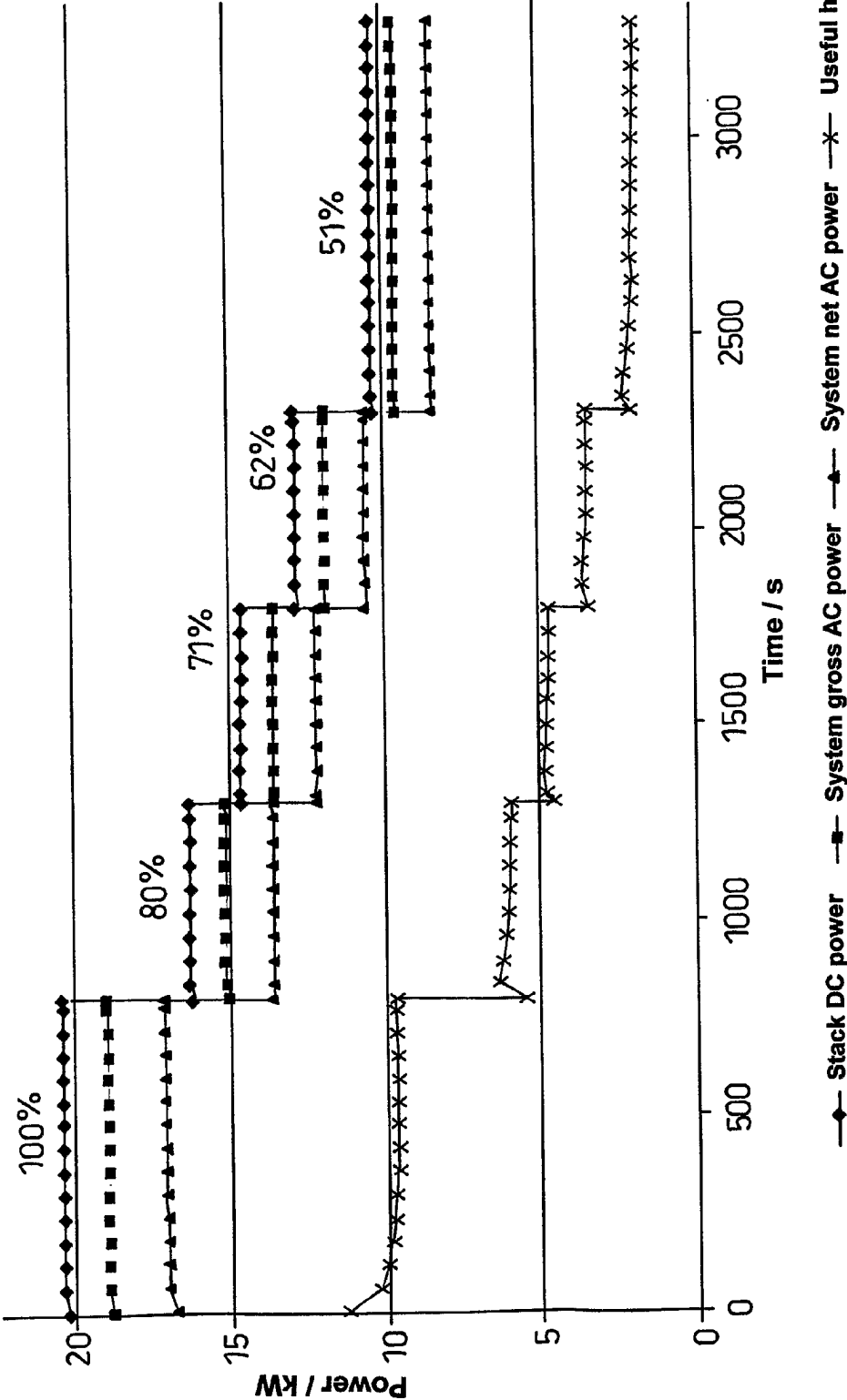


Fig. 8

9/15

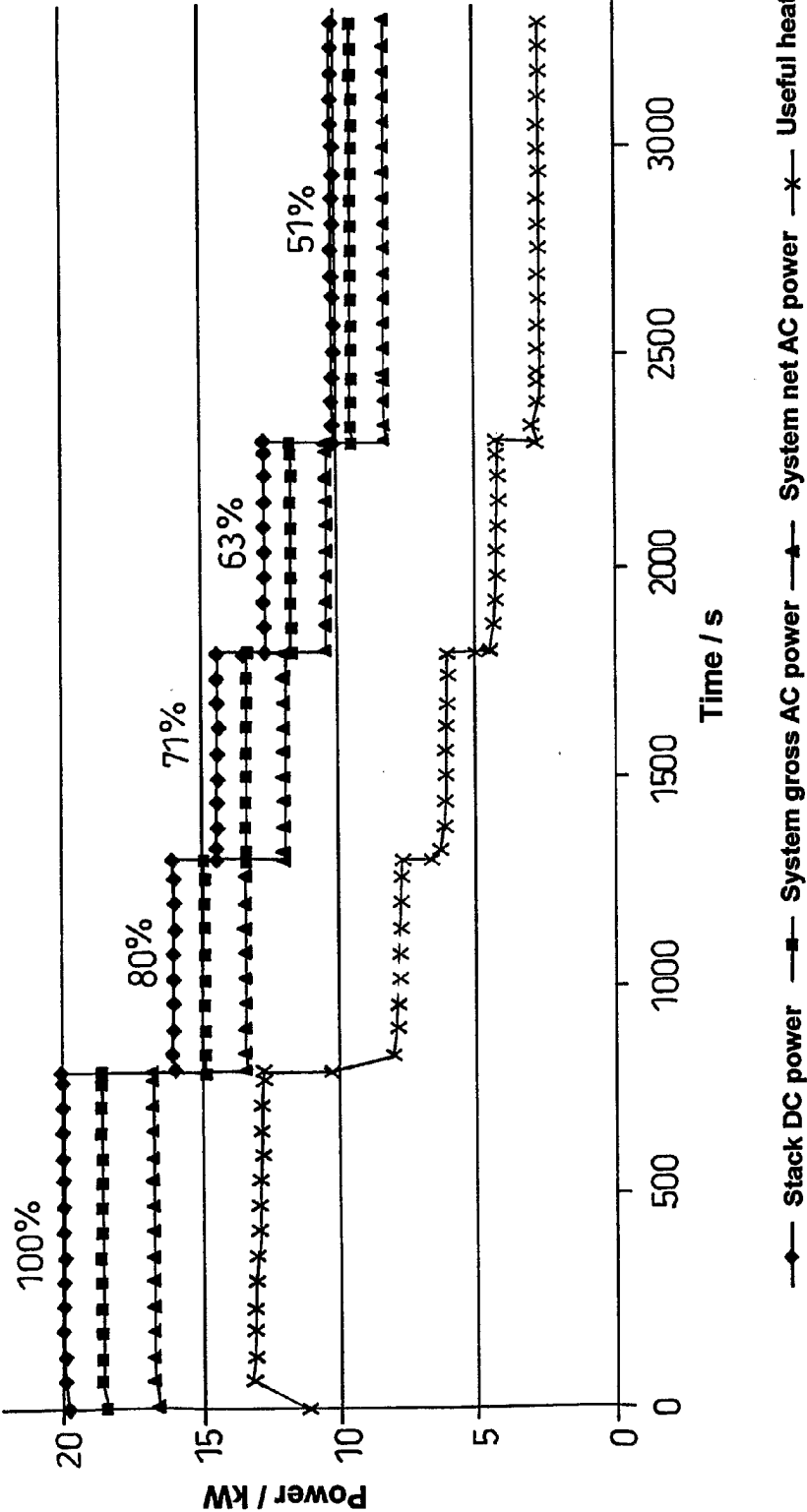


Fig. 9

10/15

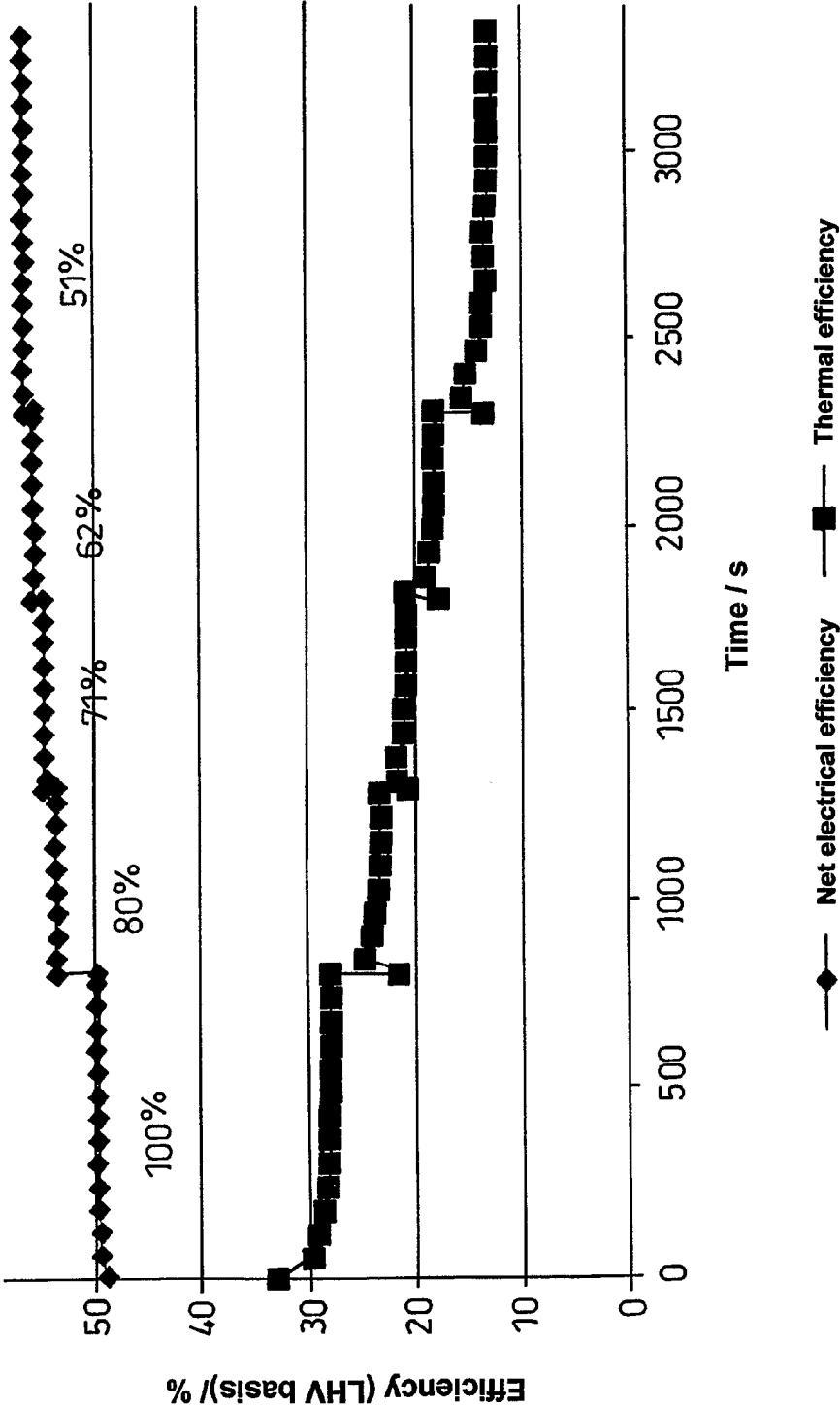


Fig. 10

11/15

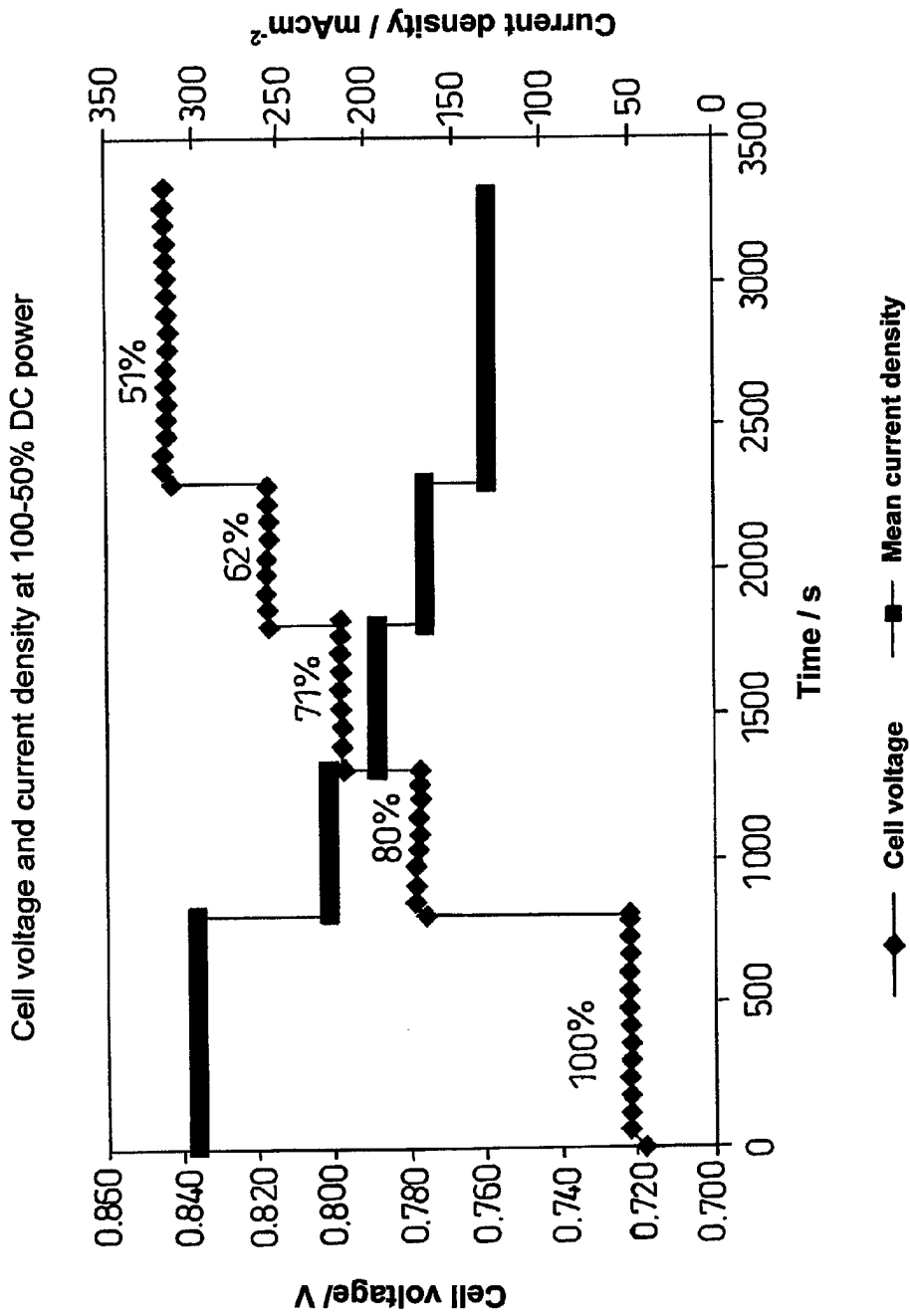


Fig. 11

12/15

Power output/use during startup procedure

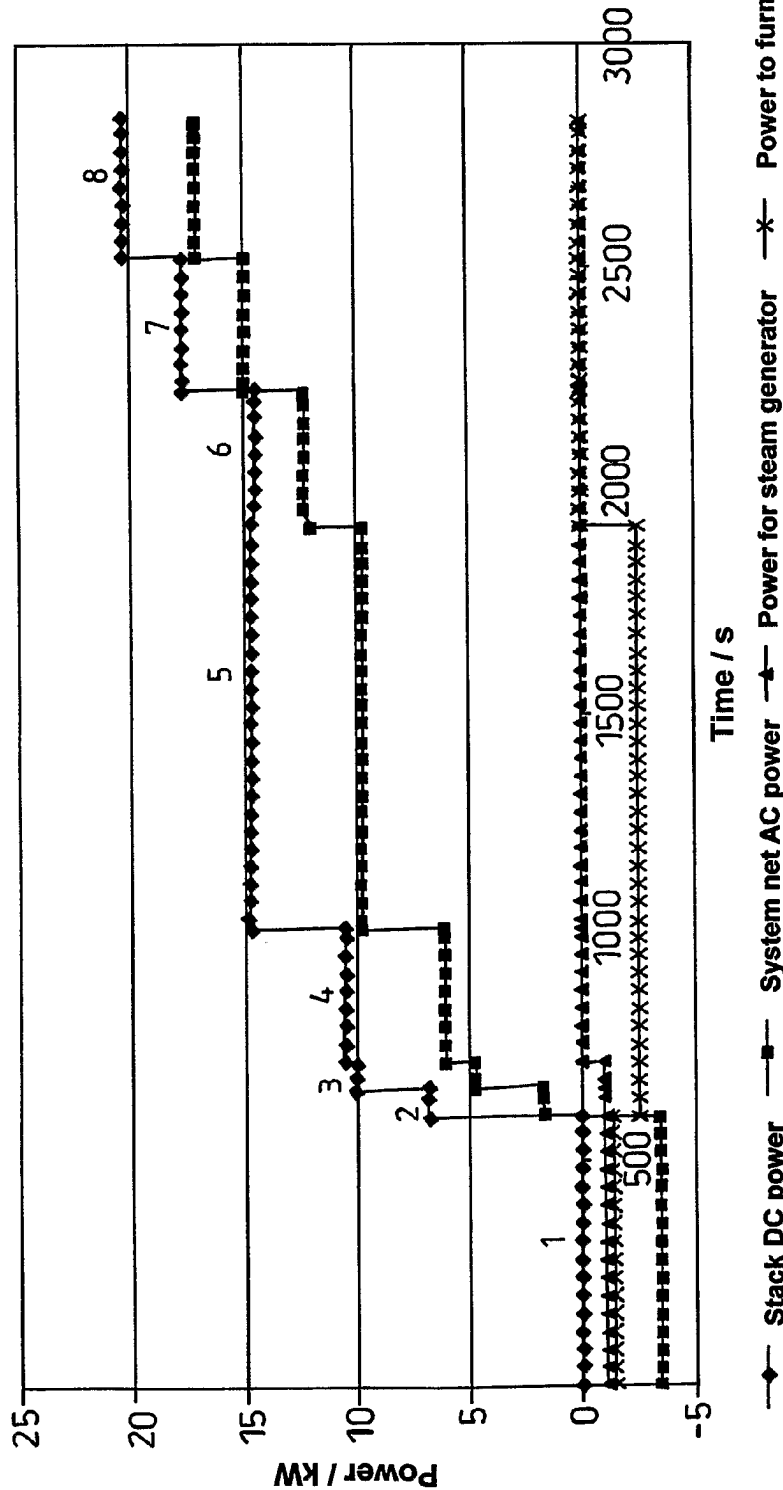


Fig. 12

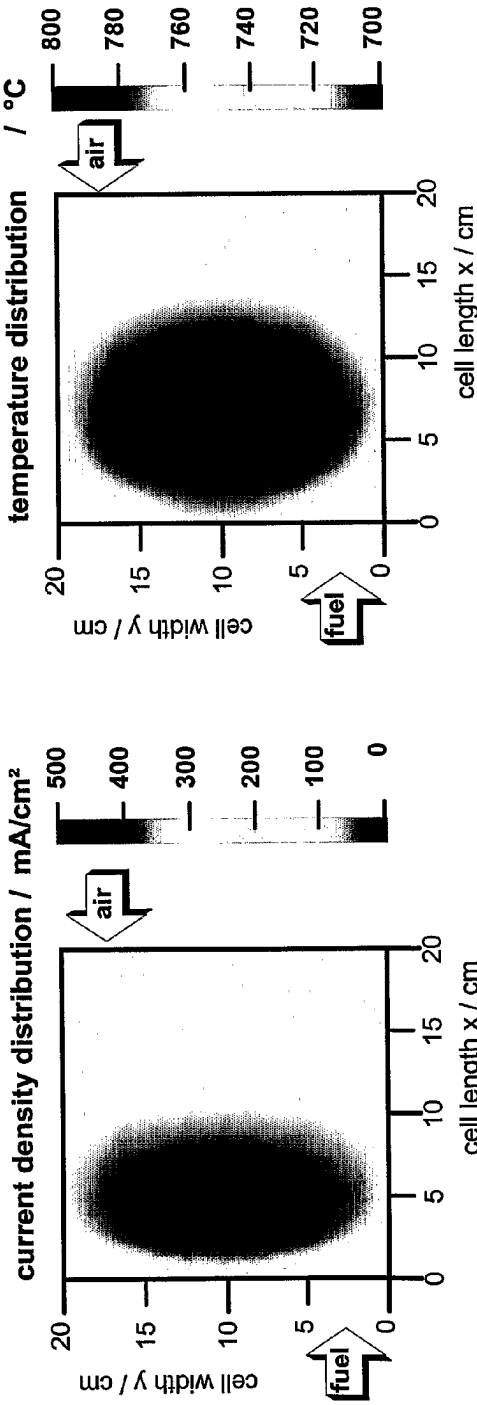


Fig. 13A

Fig. 13B

14/15

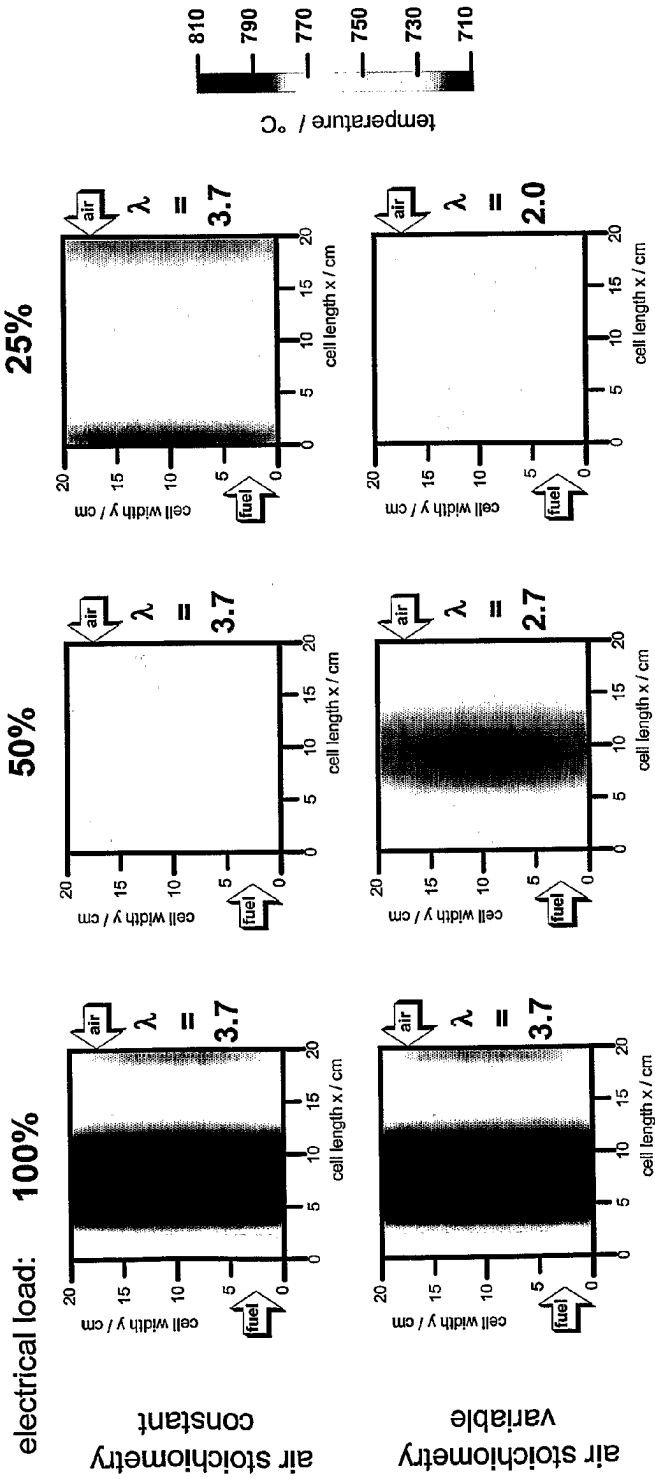
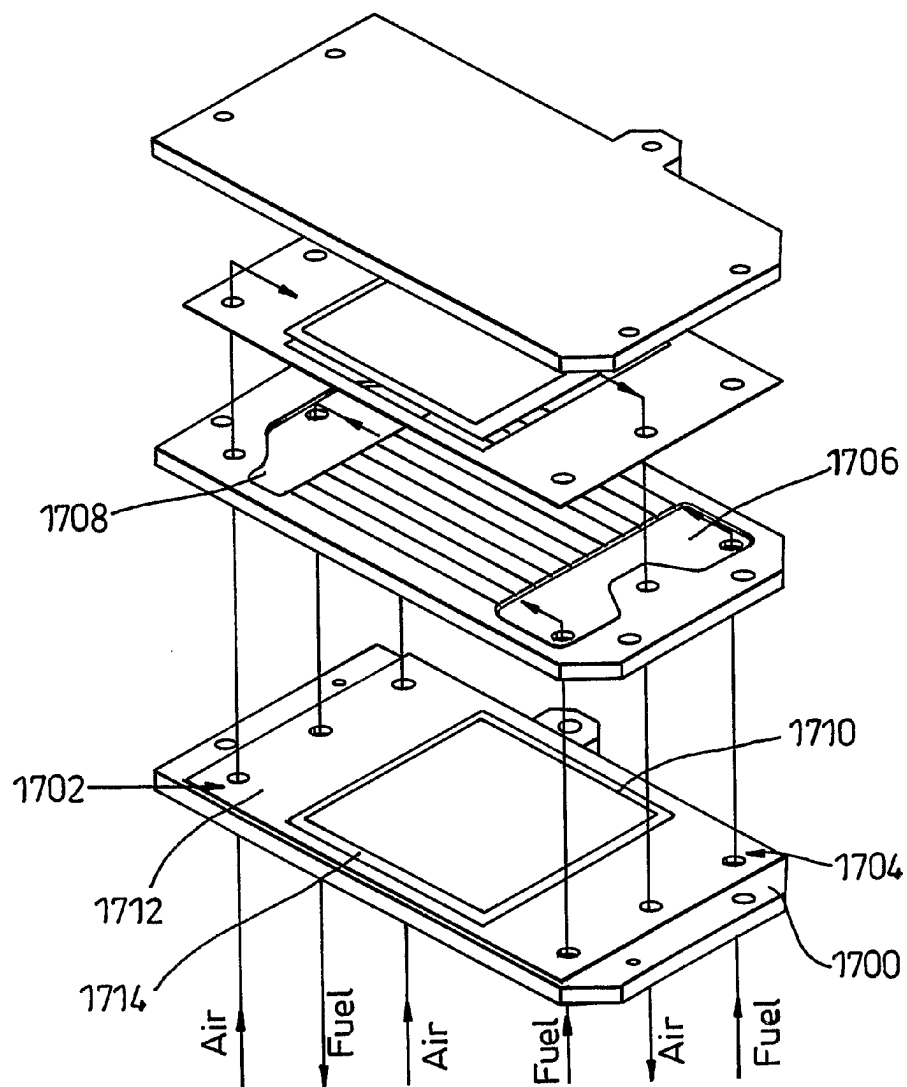


Fig. 14

15/15

**Fig. 15**